November, 1997 TAC-1997-038

Varying leptonic chemical potentials and spatial variation of primordial deuterium at high z.

A.D. Dolgov

Teoretisk Astrofysik Center

Juliane Maries Vej 30, DK-2100, Copenhagen, Denmark [1]

B.E.J. Pagel

NORDITA

Blegdamsvej 17, DK-2100, Copenhagen, Denmark

Abstract

We try to explain the spatial variation of primordial deuterium suggested by some observations by varying leptonic chemical potentials. The variation of the latter may take place in some scenarios of leptogenesis. The model predicts a large mass fraction of ^4He (35-60%) and ^7Li (up to 10^{-9}) in deuterium-rich regions. Because of lepton family symmetry, the angular variations of cosmic microwave background radiation can be sufficiently small although still observable in future measurements.

Recently several groups [1-6] have reported measurements of the deuterium abundance in Lyman-limit absorption line systems with red-shifts $0.48 < z < 3.5$ on the line of sight to quasars; these are believed to give essentially the primordial value. Surprisingly some groups have claimed a high value, $D/H \approx 2 \cdot 10^{-4}$ on the basis of ground-based data taken with the Keck telescope, but this result is now thought to be due to various errors [3] and the best value available from two "clean" systems is $3 \cdot 10^{-5}$ [5]. However, Webb et al [6] report a high deuterium abundance,

[1] Also: ITEP, Bol. Cheremushkinskaya 25, Moscow 113259, Russia.

$D/H \approx 2 \cdot 10^{-4}$, in an apparently clean system with $z = 0.7$ observed with the Hubble Space Telescope, as well as a low one in another system with $z = 0.5$, raising the possibility that there might be real spatial variations in primordial D/H.

If the effect is indeed real (which it is perhaps too early to judge), its significance is difficult to overestimate. It would strongly change our approach to primordial nucleosynthesis and possibly to the physics of the early universe. A possible variation of the light element abundances was in fact considered in ref. [7] (see also [8]), where a model of leptogenesis was considered which, first, gave a large lepton asymmetry, which could even be close to or larger than 1, and, second, this asymmetry might strongly change on astronomically large scales, l_L. The magnitude of the latter depends on the unknown parameters of the model and can easily be in the mega-giga parsec range. The model is based on the Affleck-Dine [9] scenario of baryogenesis but in contrast to the original one it gives rise to a large (and varying) lepton asymmetry and to a small baryonic one. Recently a similar model of generation of large (but not varying) lepton asymmetry was considered in ref. [10]. In what follows we will not discuss the details of the model but confine ourselves to a more phenomenological level, namely we simply assume that there exists a mechanism which created large leptonic asymmetries of order unity (electronic, muonic and/or tauonic) which vary by 100% over the distance l_L. A possible early universe scenario which would give rise to such varying and large leptonic asymmetries will be considered elsewhere. At the moment we put a less ambitious question: whether it is possible to describe the suspected spatial variation of primordial deuterium by varying chemical potentials of neutrinos without conflict with the existing astronomical data and what predictions can be made in such a model which can be tested in future observations.

To explain the claimed variation of ^2H at $z = 0.7$ the magnitude of l_L in terms of present-day units must be smaller than or close to one gigaparsec. The lower bound on this scale l_L may be much smaller. It can in principle be determined by measurements

of the abundances of light elements at large distances in our neighborhood, say, $z \geq 0.05$. It would be interesting if the scale l_L coincides with the 140/h Mpc scale observed in the large scale structure of the universe [11, 12].

Another simple possibility to explain a varying abundance of deuterium is to assume that the baryon-to-photon ratio in the universe varies as a function of position. This idea was studied in ref. [13] where it was shown that the necessary large scale isocurvature perturbations are excluded by the smallness of angular fluctuations of the cosmic microwave background radiation (CMB). A similar criticism is applicable at first sight to the model with varying lepton asymmetry. Indeed, it can be easily checked that the necessary change in chemical potential of electron neutrinos ξ_{ν_e} should be close to -1 to explain the possibly observed variation of deuterium by roughly an order of magnitude. Such a change in ξ_{ν_e} would induce a variation in total energy density during the RD stage at a per cent level, which is excluded by the smoothness of CMB. However, this objection can be avoided if there is a conspiracy between different leptonic chemical potentials such that in different spatial regions they have the same values but with interchange of electronic, muonic and/or tauonic chemical potentials. In other words we assume that in a particular spatial region the three neutrino chemical potentials have the values

$$[\xi_{\nu_e},\, \xi_{\nu_\mu},\, \xi_{\nu_\tau}] = [\alpha, \beta, \gamma]. \tag{1}$$

Then in another spatial region they should have the same values but with an arbitrary interchange of e, μ, and τ. This would ensure the same energy density at different space points and small angular variations of CMB. In fact the perturbations in CMB induced in this way would be non-vanishing and close to existing observations. We will discuss them below. Since the abundances of light elements are much more sensitive to the magnitude of the electron neutrino chemical potential than to those of muon and tauon neutrinos, the variation of ξ_{ν_e} (accompanied by corresponding variations

of ξ_{ν_μ} and ξ_{ν_τ}) would lead to a strong variation in the abundance of deuterium and other light elements.

The equality of, say, ξ_{ν_e} at one space point to ξ_{ν_μ} at another point looks like a very unnatural fine-tuning but this is not so. The present theory of elementary particles is believed to be symmetric with respect to interchange of three families of leptons. In the Affleck-Dine type scenario of generation of charge asymmetry, the latter is generated owing to the formation of baryonic (as in the original version) or leptonic charge condensates along the so called flat direction in the potential of a scalar field which possesses corresponding charges. It is rather natural to assume that the potential respects the symmetry between different lepton families. So if a flat direction corresponds to a scalar field with the combination of leptonic charges $[\alpha, \beta, \gamma]$, then there must be flat directions with the same values of the leptonic charges but interchanged with respect to e, μ, and τ. In such a model there would be regions with different values of leptonic chemical potentials which are obtained by transmutations of the original ones in (1).

The symmetry between lepton families is broken at low energy by the masses of charged leptons. So one may expect that there could be significant fluctuations of the cosmic energy density when the temperature is close to the mass of the charged tau-lepton ($m = 1777$ MeV) or to that of the muon ($m = 106$ MeV). We will see below that this is not the case. Another potential danger for a model of this kind is the variation of the energy density associated with the energy of the potential wall between the valleys (flat directions) with different leptonic charges. These domain walls however disappear because all scalar fields ϕ_l possessing different leptonic charges evolve down to the same origin of the potential where they all vanish, $\phi_l = 0$. Some remnants of the energy distortion remain but they have an energy density much smaller than that of the original domain walls.

Let us turn now to the astro-phenomenology of the model concerning the change

in the light element abundances. It is straightforward and simple to play with the standard nucleosynthesis code [14] to study the influence of different leptonic chemical potentials on the output of light elements and in Table 1 we present a number of sample calculations from which we can draw some combinations that would give a small amount of ^2H in our neighborhood (and a larger one in deuterium-rich regions). Considerations of Galactic chemical evolution [15] permit us to infer that the abundance of primordial deuterium in nearby regions where ^4He is also measured is close to the low values determined at high red-shift; we take as the best estimates for both these regions and our neighborhood $D/H = (3.2 \pm 0.8) \cdot 10^{-5}$ and $R(^4He) = 0.24 \pm 0.01$, which are well fitted in the case of no neutrino degeneracy for a baryon/photon ratio $\eta_{10} = 5 \pm 1$. An adequate fit is also obtained for the same η if we take the combination $[\xi_{\nu_e}, \xi_{\nu_\mu}] = [0, -1]$, which gives for the "mirror" region with $[\xi_{\nu_e}, \xi_{\nu_\mu}] = [-1, 0]$ a substantially higher deuterium abundance $D/H = 8.5 \cdot 10^{-5}$. This combination is not necessarily the best possible fit to the data, be the but it seems too early to look for this, bearing in mind that the observational data may change. It is worth noting that if two (or all three) ξ's are permitted to vary, the nucleosynthesis limits (for a recent reference see e.g. [16]) would be invalidated.

One can see from Table 1 that the data somewhat resist the proposed explanation. It would help if there is more deuterium in our neighborhood, $\sim 5 \cdot 10^{-5}$, and/or less in the deuterium-rich regions, $\sim 10^{-4}$. We did not try to use large values of chemical potentials because of possible problems with smoothness of CMB temperature (see below). The agreement with observations can be made better if all three chemical potentials could be adjusted as free parameters. In Table 2 we present the abundances of light elements for the *ad hoc* choice $[\xi_{\nu_e}, \xi_{\nu_\mu}, \xi_{\nu_\tau}] = [-1, 0.1, 1]$ for $\eta_{10} = 4$ and 5. The last line may not be reliable because the program fails to converge. It is noteworthy that it is possible to have, besides high ^2H and ^4He regions, regions with normal deuterium and low helium-4.

To describe simultaneously the suspected deuterium content in the rich regions and that in our neighborhood we need $\eta_{10} = 5-6$ and $\xi_{\nu_e} = 0-0.1$ in the poor regions and $\xi_{\nu_e} \approx -1.4$ in the rich regions. In this case it is possible to get D/H as large as $17 \cdot 10^{-5}$ in rich regions. The necessary value of ξ is rather high and it would be easier for the model if the deuterium fraction in rich regions would be around $10 \cdot 10^{-5}$.

A generic feature of our model is that simultaneously with high deuterium a high mass fraction of helium-4 is predicted. It is at least 30-35% or may be even above 50%. It is an interesting question what is the observational upper bound on the abundance of ^4He far away from us. All direct measurements of ^4He known to us were done at most at $z = 0.045$ corresponding to a distance of $140h^{-1}$ Mpc[17]. A very large mass fraction of ^4He can possibly be excluded with the help of star and galaxy evolution. Stars should be brighter and have a shorter life-time. All data indicate that distant objects (including quasars) have more or less normal chemical content. Still we do not know what is the permitted mass fraction of helium-4 which does not contradict the data. This would be the subject of a separate study. Presumably 35% of ^4He in some distant parts of the universe is not excluded. As for much higher values, we do not have an answer now.

A very sensitive indicator of any inhomogeneities in the universe is the cosmic microwave background. The bearers of electronic, muonic, and tauonic chemical potentials have different masses: though different neutrinos are most probably very light or even massless, so that their contribution to the energy density is the same, the masses of the corresponding charged leptons are very much different and this could be potentially dangerous for the model. This is not the case, however, as can be seen from the following considerations. Let us assume for simplicity that there are only two lepton families, electronic and muonic. Let us assume also that the primeval plasma has nonzero electronic and muonic charge densities, D_e and D_μ. Of course the plasma is electrically neutral. Thermal equilibrium in the plasma is fulfilled with a very good

accuracy (at least for temperatures above 3 MeV, when neutrinos decouple). The distributions of different particles are given by the normal Fermi (or Bose) functions with nonzero chemical potentials which permit to have nonzero D_e and D_μ. Due to reactions $e^- + \bar\nu_e \leftrightarrow \mu^- + \bar\nu_\mu$ and similar (crossed) ones, the following relation between chemical potentials must be fulfilled in thermal equilibrium:

$$\xi_e - \xi_{\nu_e} = \xi_\mu - \xi_{\nu_\mu} \tag{2}$$

There is also the condition of electric neutrality of the plasma:

$$\delta n_e + \delta n_\mu = 0 \tag{3}$$

and the expressions for electronic and muonic charge densities:

$$\delta n_e + \delta n_{\nu_e} = D_e \tag{4}$$

and

$$\delta n_\mu + \delta n_{\nu_\mu} = D_\mu \tag{5}$$

where $\delta n_a = n_a - n_{\bar a}$ is the difference in number densities of particles and antiparticles with

$$n_a = \int \frac{d^3p}{1+\exp(E/T - \xi_a)} \tag{6}$$

The number density of antiparticles is given by the same expression with the opposite sign of ξ_a.

One can see from the symmetry property of the system of equations (2-5) that for any solution corresponding to the set $[D_e, D_\mu] = [\alpha, \beta]$ there exists the mirror solution corresponding to the set $[D_e, D_\mu] = [\beta, \alpha]$ which can be constructed from the original solution by the substitution: $\delta n_e \leftrightarrow -\delta n_e$, $\delta n_\mu \leftrightarrow -\delta n_\mu$ (correspondingly $\xi_{e,\mu} \leftrightarrow -\xi_{e,\mu}$) and $\delta n_{\nu_e} \leftrightarrow \delta n_{\nu_\mu}$. Evidently the energy densities of both solutions are the same.

There are some other possible inhomogeneities in the energy density that could be either dangerous for the model or observable in CMB. The first and most evident one is related to the binding energy of ^4He, which is 7 MeV per nucleon. Since the mass fraction of ^4He may change by a factor of 2 in deuterium- (and helium-) rich regions (from 25% to more than 50%), this means that the variation in baryonic energy density may be as large as $2 \cdot 10^{-3}$. The contribution of baryons to the total energy density is given by $\Omega_B = 3\%(\eta/4)(0.65/h)^2$, so the relative density fluctuations are at most

$$\frac{\delta\rho}{\rho_{tot}} = 6 \cdot 10^{-5}(\eta/4)(0.65/h)^2 \tag{7}$$

To estimate the fluctuations in CMB temperature we can use the results of ref. [13], where similar isocurvature density perturbations, but with amplitude $(2 \cdot 10^{-3})^{-1} = 500\times$ larger, were considered. According to their results normalized to our smaller perturbations

$$\frac{\delta T}{T} = 10^{-5}\left(\frac{\lambda_0}{10\lambda}\right)^2 \tag{8}$$

where $\lambda_0 = c/H_0 = 3\text{Gpc}/h$. So the anisotropy induced by the Sachs-Wolfe effect would be below the observational bounds for scales above $\sim 300h^{-1}$ Mpc. If D/H in the rich regions is about 10^{-4} (and not $2 \cdot 10^{-4}$), then the variation of helium-4 could be smaller. Correspondingly smaller density perturbations would be induced. In this case smaller scales in fluctuations of CMB temperature, down to $\sim 150h^{-1}$ Mpc, would be permitted. However, on scales below 2^o (or below 200 Mpc), the result (8) would not be valid. These scales are dominated by Doppler shift across the fluctuations at the surface of last scattering [18]. The measurements on small scales permit possibly $\delta T/T = 3 \cdot 10^{-5}$, which could also be compatible with this model. Such fluctuations may be observed in the future MAP or PLANCK missions or with balloons.

There is another effect which is more subtle theoretically but which could also

give rise to similar fluctuations in $\delta T/T$. The energy densities of electron and muon neutrinos are known [19, 20] to be different owing to the following effect. After neutrinos decoupled from the primeval plasma, which roughly took place at $T = 2$ MeV for electron neutrinos and at $T = 3$ MeV for muonic and tauonic ones, the temperatures of electrons and photons became somewhat different from the neutrino temperature owing to heating of the electromagnetic component of the plasma by e^+e^--annihilation into photons. Because of this temperature difference and due to residual e^+e^--annihilation into $\nu\bar{\nu}$, the usually assumed equilibrium neutrino distributions became slightly distorted. The nonequilibrium correction to the energy density of electron neutrinos in the standard model is approximately [21]:

$$\Delta\rho_{\nu_e}/\rho_\nu \approx 0.9\% \tag{9}$$

and the distortion of the energy density of muon and tauon neutrinos is

$$\Delta\rho_{\nu_\mu}/\rho_\nu = \Delta\rho_{\nu_\tau}/\rho_\nu \approx 0.4\% \tag{10}$$

(closely similar results are obtained in ref. [22]). The difference between ν_e and $\nu_{\mu,\tau}$ is related to a greater efficiency of the process $e^+e^- \to \nu\bar{\nu}$ due to the presence of charged current interactions only for ν_e. Now because of nonzero leptonic chemical potentials these results would slightly change. They would remain the same in the Boltzmann approximation because the probability of e^+e^--annihilation into $\nu\bar{\nu}$ does not depend on the chemical potential of neutrinos in the case of Boltzmann statistics. Typically corrections due to Fermi statistics are about 10%. So the relative efficiency of annihilation due to nonzero chemical potentials becomes smaller by approximately $0.1[\cosh(\xi) - 1]$. This expression is true for relatively small ξ, $\xi \leq 1$; for larger ξ it is changed to a power law.

To get an estimate of the magnitude of the density fluctuations due to variation of chemical potentials let us assume that in our neighborhood the chemical potentials

have the values $\xi_{\nu_e} = \xi_{\nu_\tau} = 0$ and $\xi_{\nu_\mu} = -1$ and in the deuterium-rich region they are $\xi_{\nu_\mu} = \xi_{\nu_\tau} = 0$ and $\xi_{\nu_e} = -1$. Thus the relative energy density of neutrinos changes by

$$\frac{\delta\rho_\nu^{(tot)}}{\rho_\nu} = \delta\left(\frac{\Delta\rho_{\nu_e}}{\rho_\nu} + \frac{\Delta\rho_{\nu_\mu}}{\rho_\nu} + \frac{\Delta\rho_{\nu_\tau}}{\rho_\nu}\right) = (0.9\% - 0.4\%)\cdot 0.1(\cosh\xi - 1) \sim 2.5\cdot 10^{-4} \quad (11)$$

Keeping in mind that one neutrino species contributes 10-20 % to the total energy density during the RD stage, we find that the relative density fluctuations of neutrinos due to variation of chemical potentials are approximately $\delta\rho_\nu/\rho_{tot} \approx 5\cdot 10^{-5}$. In fact the fluctuations of the total energy density are very much smaller than that because the increase in ρ_ν is accompanied by a similar decrease in the energy density of photons and $e^\pm$. Thus the phenomenon we discuss gives rise to a rather peculiar perturbation: the variation of the total energy density is negligibly small but the radiation temperature varies between different spatial points.

As was calculated in ref. [21] the photon temperature drops in comparison with the standard one by 10^{-3}, due to the above mentioned transfer of energy from the electromagnetic component of the plasma to neutrinos. This change of temperature should be proportional in a crude approximation to the above mentioned change of neutrino energy:

$$\frac{\Delta T}{T} \approx 0.1\frac{\Delta\rho_\nu^{(tot)}}{\rho_\nu} \sim 10^{-3} \quad (12)$$

Now if chemical potentials are not spatially constant, the quantity $\Delta\rho_\nu^{(tot)}/\rho_\nu$ would vary together with the chemical potentials at different points. Its variation is given by eq. (11). Accordingly the variation of the photon temperature due to this effect is

$$\frac{\delta T}{T} = \delta\left(0.1\frac{\Delta\rho_\nu^{(tot)}}{\rho_\nu}\right) \approx 5\cdot 10^{-5}(\cosh\xi - 1) \sim 2.5\cdot 10^{-5} \quad (13)$$

which is close to the observational bounds.

These are of course very crude estimates. The real result should be somewhat smaller. An account of inverse annihilation, $\bar\nu_e\nu_e \to e^- e^+$ and of elastic νe-scattering results in a smoothing down of the spectral distortion. An estimate of these "inverse"

effects, made along the lines of semi-analytical estimates of ref. [19], diminishes the temperature change by a factor of roughly 2/3.

The magnitude of temperature fluctuations depends in particular on the unknown values of the ξ's. For example for $|\xi| = 0.7$ the effect would be twice smaller than for $|\xi| = 1$, while for $|\xi| = 1.4$ it is twice bigger. We take $|\xi| = 1.4$ as an upper limit for the magnitude of possible variations of chemical potentials. To be on the safe side we possibly need somewhat smaller ξ's and correspondingly a fraction of deuterium in the rich regions of about 10^{-4}. A rigorous calculation of the effect is a straightforward but formidable numerical problem. It seems premature to do that at this stage. However, we will have to do the calculations if the effect of spatial variation in deuterium abundances is confirmed and the predicted variation of helium-4 is either found or not ruled out.

To conclude, we try to explain a spatial variation of primordial deuterium, that has perhaps been observed, by varying leptonic chemical potentials. The model could be confirmed (or rejected) by looking for a very large mass fraction of primordial helium-4 in deuterium-rich regions but this is not a practical possibility in the context of data available now or in the near future. A more promising test seems to be possible from the theory of stellar evolution with a high mass fraction of ^4He. The hypothesis also predicts larger abundances of other light elements in these regions, e.g. ^7Li should be at the level of 10^{-9}. There might be also regions with normal deuterium and low helium-4. If there is a family symmetry which ensures permutational symmetry for different chemical potentials, a very large distortion of CMB isotropy can be avoided, but there still remain nonzero $\delta T/T$ fluctuations which can be detected if the higher abundances of deuterium and other elements (in particular ^4He) exist. It is a curious coincidence that the theory of large scale structure formation may possibly favor neutrino chemical potentials [23] close to those that are needed in our model.

Acknowledgments The work of A.D. was supported by Danmarks Grundforskningsfond through its funding of the Theoretical Astrophysical Center. We thank I. Novikov and J. Madsen for stimulating comments.

References

[1] D. Tytler, X-M. Fan, and S. Burles, Nature **381** (1996) 207.

[2] M. Rugers and C.J. Hogan, Astrophys. J. **469** (1996) L1.

[3] D. Tytler, S. Burles, and D. Kirkman, asto-ph/9612121.

[4] A. Songalia, E.J. Wampler, and L.L. Cowie, Nature **385** (1997) 137.

[5] D. Tytler, IAU Symposium 187. Cosmic Chemical Evolution, Kluwer (1998).

[6] J.K. Webb, R.F. Carswell, K.M.Lanzetta, et al. Nature, **388** (1997) 250.

[7] A.D.Dolgov and D.K.Kirilova, J.Moscow Phys.Soc., **1** (1991) 217.

[8] A.D.Dolgov, Phys.Repts **222** (1992) No. 6.

[9] I. Affleck and M. Dine, Nucl. Phys. **B249** (1985) 361.

[10] A. Casas, W.Y. Cheng, and G. Gelmini, hep-ph/9709289.

[11] M. Einasto, J. Einasto, E. Tago et al, MNRAS **269** (1994) 301.

[12] A. Ratcliffe, T. Shanks, A. Broadbent et al, MNRAS **281** (1996) L47.

[13] C.J. Copi, K.A. Olive, and D.N. Schramm, astro-ph/9606156.

[14] L. Kawano, Fermilab-Pub-92/04-A (1992).

[15] B.E.J. Pagel, "Nucleosynthesis and Chemical Evolution of Galaxies", Cambridge University Press, 1997.

[16] K. Kohri, M. Kawasaki, and K. Sato, astro-ph/9612237.

[17] Y.I. Izotov, T.X. Thuan, and V.A. Lipovetsky, Ap. J. Suppl. **108** (1997) 1.

[18] J. Silk, Phys. Scr. **36** (1991) 16.

[19] A.D. Dolgov and M. Fukugita, JETP Lett. **56** (1992) 123; Phys. Rev. D **46** (1992) 5378.

[20] S. Dodelson and M.S. Turner, Phys. Rev. D **46** (1992) 3372.

[21] A.D. Dolgov, S.H. Hansen, and D.V. Semikoz, Nucl. Phys. **B503** (1997) 426.

[22] S. Hannestad and J. Madsen, Phys. Rev. D **52** (1995) 1764.

[23] G.B. Larsen and J. Madsen, Phys. Rev. D **52** (1995) 4282.

η_{10}	ξ_{ν_e}	ξ_{ν_μ}	ξ_{ν_τ}	$10^5 \frac{D}{H}$	Y_p	$10^{10} \frac{^7Li}{H}$
4	0	0	0	5.03	0.242	1.85
	0	-1	0	7.33	0.248	1.78
	-1	0	0	12.1	0.539	4.45
	0	-1.3	0	5.56	0.252	1.74
	-1.3	0	0	20.0	0.644	10.6
	0.1	-1	0	5.07	0.224	1.66
	-1	0.1	0	12.1	0.539	4.45
	0.1	-1.3	0	5.27	0.228	1.62
	-1.3	0.1	0	20.0	0.644	10.6
5	0	0	0	3.55	0.244	2.95
	0	-1	0	3.76	0.250	2.82
	-1	0	0	8.50	0.544	4.40
	0	-1.4	0	3.98	0.256	2.70
	-1.4	0	0	17.1	0.686	10.9
	0.1	-1	0	3.57	0.226	2.64
	-1	0.1	0	8.51	0.544	4.40
	0.1	-1.4	0	3.78	0.231	2.53
	-1.4	0.1	0	17.2	0.686	10.9
6	0	0	0	2.65	0.246	4.35
	0	-1	0	2.82	0.252	4.17
	-1	0	0	6.40	0.548	5.36
	0	-1.4	0	2.98	0.258	3.99
	-1.4	0	0	12.8	0.692	8.83
	0.1	-1	0	2.67	0.228	3.90
	-1	0.1	0	6.41	0.548	5.36
	0.1	-1.4	0	2.83	0.233	3.74
	-1.4	0.1	0	12.8	0.692	8.84

Table 1: Abundances of light elements for different values of the baryon number density, $\eta = 10^{10} n_B/n_\gamma$ and neutrino chemical potentials ξ_{ν_a}.

η_{10}	ξ_{ν_e}	ξ_{ν_μ}	ξ_{ν_τ}	$10^5\,\frac{D}{H}$	Y_p	$10^{10}\,\frac{^7Li}{H}$
4	0.1	-1	1	5.35	0.229	1.61
	-1	0.1	1	13.2	0.548	4.84
	1	-1	0.1	3.98	0.080	0.70
5	0.1	-1	1	3.77	0.231	2.54
	-1	0.1	1	9.21	0.553	4.49
	1	-1	0.1	2.80	0.081	1.12

Table 2: Abundances of light elements for $\eta = 10^{10} n_B/n_\gamma = 4,\ 5$ and nonzero values of all three neutrino chemical potentials ξ_{ν_a}.